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Enhancement of ϕ mesons in $p + \text{Pb}$ and $\text{Pb} + \text{Pb}$ collisions at 158 A GeV/c

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Abstract

Using a hadron-string cascade model LUCIAE, the ϕ -meson production in nuclear collisions ($p + \text{Pb}$ and $\text{Pb} + \text{Pb}$) and elementary collisions $p + p$ were studied systematically. Within the framework of the model, the experimentally measured ϕ enhancement in $p + \text{Pb}$ and $\text{Pb} + \text{Pb}$ over $p + p$ collisions can be mostly explained by the collective effects in the gluon string emission and the reduction of the s -quark suppression. © 2001 Published by Elsevier Science B.V.

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Already suggested in the early eighties [1] strangeness enhancement is presently considered as one of the most promising signatures for the creation of a Quark–Gluon Plasma (QGP) phase in relativistic nuclear collisions. At the CERN SPS the WA97 Collaboration has measured a clear enhancement of multi-strange baryons (Λ , Ξ , Ω) in 158 A GeV/c $\text{Pb} + \text{Pb}$ collisions relative to $p + \text{Pb}$ collisions [2]. As the mesonic counterpart, also an enhancement of the ϕ -meson production in relativistic nuclear collisions was suggested as an evidence of the QGP formation in Ref. [3], since in the environment of a QGP the copious strange

and antistrange quarks originating from gluon annihilation would be very likely to coalesce forming ϕ -mesons during the hadronization period. Due to the small cross sections of ϕ -mesons interacting with non-strange hadrons [1,3], penetrating ϕ -mesons are also messengers of the early stage of the colliding system. Thus, the ϕ -meson is not only a promising signature for the QGP formation but also a good probe to study the reaction dynamics.

Strangeness enhancement in relativistic nucleus–nucleus collisions has in the meantime been investigated by various types of models, besides LUCIAE [4,5]. These are: thermal models assuming an equilibrated quark–gluon plasma phase [6–8], the non-equilibrium hadron gas model with a hadronic

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strangeness saturation factor [9], the RQMD [10] and SFM [11] models including the fusion of overlapping strings, HIJING [12] and HIJING with modifications of the baryon junction exchange mechanism [13], UrQMD with a reduction of the constituent quark masses [14] or with a strong colour field effect [15], the diquark breaking model [16], and the model of strangeness content in nucleon [17], etc.

Recently, NA49 measured the ϕ yield, the rapidity and transverse mass distributions in $p + p$, $p + \text{Pb}$ and $\text{Pb} + \text{Pb}$ collisions at 158 A GeV/c [18]. The model studies on the ϕ -meson enhancement in relativistic nucleus–nucleus collisions are rare and to our knowledge there exists up to now no theoretical description of the full set of NA49 data on the ϕ production. In this Letter we use a hadron and string cascade model, LUCIAE [19], in order to investigate their data and the enhancement mechanism especially. We have successfully used LUCIAE to study the enhanced production of multi-strange baryons (Λ , Ξ , Ω) and determined the model parameters related to the production of strange particles [4,5]. Therefore, there is no additional free parameter in the present calculations for ϕ -meson production.

The LUCIAE model is based on FRITIOF [20], which is an incoherent hadron multiple scattering and string fragmentation model. In FRITIOF, the nucleus–nucleus collision is depicted simply as a superposition of nucleon–nucleon collisions. What characterises LUCIAE beyond FRITIOF are the following features: first of all, the rescattering between the participant and spectator nucleons and the produced particles from the string fragmentation processes are generally taken into account [21]. However, as proposed in [1,3] we, in this work, assume that the final state interaction plays no significant role for the ϕ production. Thus, effects of the final state interactions on the ϕ -meson production and propagation are neglected. Secondly, the collective effect in the gluon emission of strings is considered by so-called firecracker model [22]. In relativistic heavy ion collisions the string density can be quite high such that some strings might form a collective state. Such a string state may emit gluons using its larger common energy density. Thirdly, a phenomenological mechanism for the reduction of the s -quark suppression in the string fragmentation process [4] is introduced. It is well known that the s -quark suppression factor (the suppression of s -quark pair produc-

tion with respect to u or d pair production in the string fragmentation), i.e., the parameter $parj(2)$ in JETSET which runs together with FRITIOF and deals with the string fragmentation, is not a constant but energy dependent in hadron–hadron collisions [4,9]. In $p + A$ and $A + A$ collisions $parj(2)$ depends even on the size and centrality of collision system as a result of mini-jet (gluon) production stemming from the string–string interactions. The phenomenological mechanism introduced in [4] considers all of the above facts via the effective string tension and therefore the pertained JETSET parameters. The extra model parameters introduced were fixed by fitting to $p + p$ data [4].

In Table 1 the LUCIAE results for the ϕ -meson yield and the average multiplicities of π^+ and π^- , etc. are compared to the NA49 data. It should be mentioned here that the pion multiplicities were quoted by NA49 from [23] where the experiment triggers on the total inelastic reaction cross section while only 91% of this cross section was measured in the NA49 experiment. Thus, a correction must be made which is referred to as ‘after correction’ in Table 1. The experimental results for the ϕ -enhancement factor

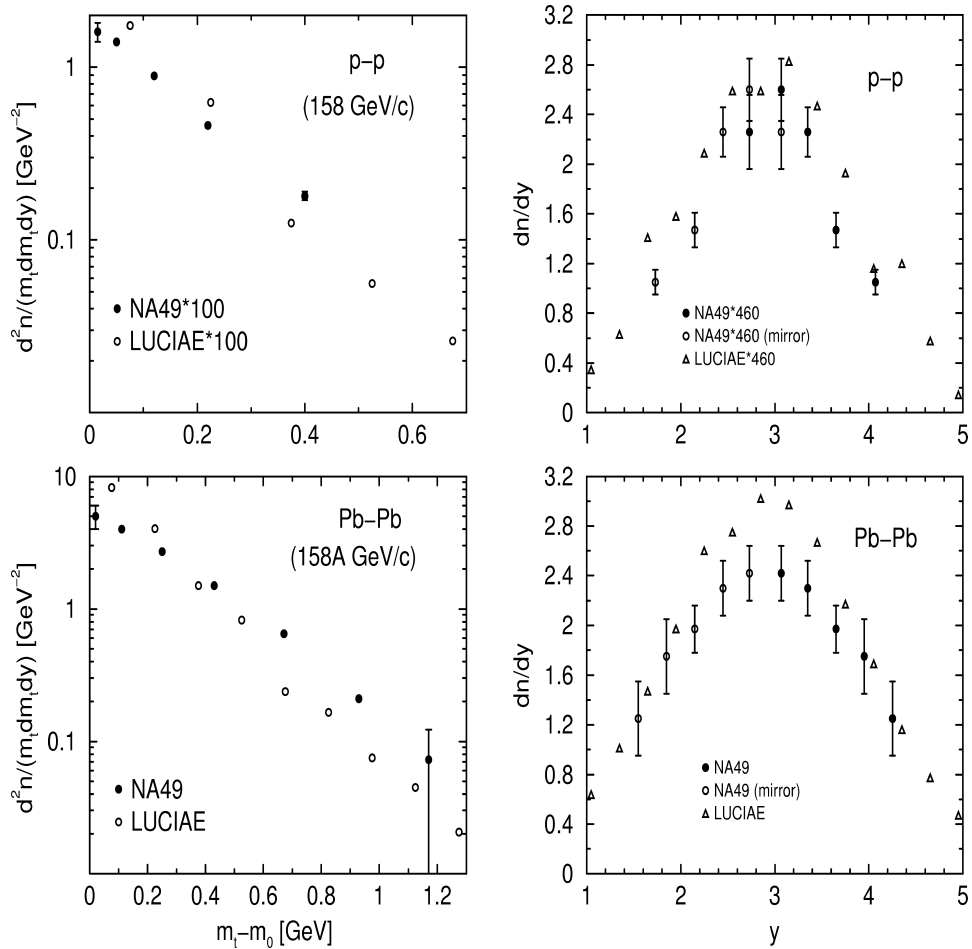
$$E_{\text{reaction}} = \frac{\langle\phi\rangle/\langle\pi\rangle(\text{reaction})}{\langle\phi\rangle/\langle\pi\rangle(p + p \text{ inelastic})} \quad (1)$$

[18], in minimum bias $p + \text{Pb}$ and central $\text{Pb} + \text{Pb}$ relative to $p + p$ after correction are 1.55 and 2.7 ± 0.7 and the corresponding LUCIAE results are 1.54 and 2.2 , respectively. It seems to indicate that the strangeness enhancement which is already present in $p + A$ collisions [24] can be reproduced with LUCIAE. The transverse mass distributions and the rapidity distributions of ϕ -mesons in $p + p$ and $\text{Pb} + \text{Pb}$ collisions at momentum 158 GeV/c per nucleon are compared in Fig. 1. Fitting rapidity distributions obtained from LUCIAE with a Gaussian, $f(y) = c \times \exp(-(y - y_{\text{cm}})^2/2\sigma^2)$, one obtains $\sigma = 0.967$ ($p + p$) and 1.05 ($\text{Pb} + \text{Pb}$), which should be compared with the NA49 results of 0.89 ± 0.06 and 1.22 ± 0.16 , respectively. Since the inverse slope parameter T extracted from the transverse mass distributions is very sensitive to the details of the fitting procedure we fit the highest four m_t data points both for the NA49 and LUCIAE transverse mass distributions of $\text{Pb} + \text{Pb}$ collisions with an exponential of the form $f(m_t) = c \times \exp(-m_t/T)$. We obtain then $T_{\text{NA49}} = 289$ MeV and $T_{\text{LUCIAE}} = 212$ MeV. For $p + p$, if one fits the

Table 1

Average multiplicities of particles in an event (momentum 158 GeV/c per nucleon)

		n_{ch}	n_{π}	n_{ϕ}	n_{ϕ}/n_{π}
$p + p$	NA49	7.2	2.87^1	0.012 ± 0.0015	0.00418 ± 0.00053
			2.61^2		0.00460 ± 0.00053^2
$p + Pb^3$	LUCIAE	7.82	2.67	0.0141	0.00528
	NA49				0.00714
	LUCIAE	22.8	6.88	0.0559	0.00812
Pb + Pb	NA49		611	7.6 ± 1.1	0.0124 ± 0.0018
	LUCIAE		679	7.89	0.0116

¹ Taken from Nucl. Phys. B 84 (1975) 269 by NA49.² After correction for the trigger of pions.³ Minimum bias.Fig. 1. Transverse mass distributions (left side) and rapidity distributions (right side, $3.0 < y < 3.8$ for $p + p$ and $2.9 < y < 4.4$ for Pb + Pb) of ϕ -mesons in $p + p$ (upper panels) and Pb + Pb (lower panels) collisions at 158 A GeV/c.

highest three m_t data points both for the NA49 and LUCIAE results one obtains nearly the same inverse slope parameter $T = 189$ MeV. To further improve the agreement between the data and LUCIAE results one might need to invoke the intrinsic transverse momentum broadening in the string fragmentation [25] provided the rescattering of ϕ -meson is not important. However, one sees from Table 1 and Fig. 1 that employing the mechanisms of collective string effects in the gluon emission and the reduction of the s -quark suppression in the string fragmentation process, LUCIAE is able to describe, to certain extent, the data for $p + p$, $p + \text{Pb}$, and $\text{Pb} + \text{Pb}$ collisions consistently.

The roles of the mechanisms of the collective effect in the gluon emission of strings and the reduction of the s -quark suppression in string fragmentation in the ϕ enhancement are investigated in Table 2. In order to understand the results shown in Table 2 the JETSET parameters relevant to the effective string tension are given in Table 3. These are the parameters $parj(1)$, $parj(3)$ and $parj(21)$, besides $parj(2)$. $parj(1)$ stands for the suppression of diquark–antidiquark pair production compared to the quark–antiquark pair production in the string fragmentation, $parj(2)$ is the suppression of s -quark pair production with respect

to u or d pair production, $parj(3)$ refers to the extra suppression of strange diquark production compared to the normal suppression of the strange quark. Finally $parj(21)$ is the width of the Gaussian transverse momentum distribution of $q\bar{q}$ pairs in the string fragmentation.

The values of these parameters given in the second or fourth line of Table 3 are the default values in JETSET. The mechanism of the reduction of s -quark suppression is considered in a phenomenological way where the effective string tension is linked mainly to the transverse momentum of the hardest gluon on a string [4]. In the case without the firecracker mechanism, but with the reduction of s -quark suppression, the transverse momentum of gluons on a string is small and thus the values of the JETSET parameters are smaller than the default values, correspondingly (cf. lines three and four of Table 3). That is the reason why the ϕ -meson yield in case without firecracker but with the reduction of s -quark suppression is even lower than in the case without both, firecracker and the reduction of s -quark suppression (cf. lines three and four of Table 2). A note is in order here, LUCIAE calculations with the default JETSET parameters which are determined using e^+e^- data overestimate the production of strange particles in $p + p$ collisions [4], which is the very reason that we proposed a phenomenological mechanism to investigate how the string tension varies as a function of the collision energy in $p + p$ collisions. One can see from Tables 1 and 2 that the firecracker model plays the major role and the reduction of s -quark suppression is significant only in combination with the firecracker model.

It is interesting to compare LUCIAE [4] with UrQMD [14,15] in the mechanism of strangeness enhancement. Both of them start from the quantum tunnelling probability

$$\exp\left(\frac{-\pi m^2}{\kappa}\right) \exp\left(\frac{-\pi p_t^2}{\kappa}\right) \quad (2)$$

for the production of $q\bar{q}$ pair with the quark mass m and the transverse momentum p_t from a string of string tension κ [26]. Thus, the suppression factor of the $s\bar{s}$ pair production with respect to u or d pair, for instance, can be expressed as

$$parj(2) = \exp\left(\frac{-\pi(m_s^2 - m_u^2)}{\kappa}\right). \quad (3)$$

Table 2

Average multiplicities of particles in an event of central Pb + Pb collisions at 158 A GeV/c

	n_π	n_ϕ	n_ϕ/n_π
LUCIAE	679	7.89	0.0116
w/o s^1	687	6.28	0.00914
w/o f^2	679	4.29	0.00632
w/o s and f	643	5.48	0.00852

¹ Without reduction of s quark suppression.

² Without firecracker.

Table 3

The values of four JETSET parameters in central Pb + Pb collisions at 158 A GeV/c

	$parj(1)$	$parj(2)$	$parj(3)$	$parj(21)$
LUCIAE	0.116	0.313	0.409	0.373
w/o s	0.100	0.300	0.400	0.320
w/o f	0.0497	0.215	0.313	0.318
w/o s and f	0.100	0.300	0.400	0.320

In [14,15] it was then argued that in the relativistic $A + A$ collisions the string tension should be three times larger than that in $p + p$ collisions at the same energy due to the higher string density. The increase of the string tension is further attributed to the reduced quark mass stemming possibly from a transition of chiral restoration [14]. On the other hand, in [4] an effective string tension was introduced and is phenomenologically related to the multi-gluon string in comparison with the pure $q\bar{q}$ string. Consequently the effective string tension and the pertained JETSET parameters are increasing with the energy, the size and centrality of collision system. Therefore, strangeness production in relativistic $p + p$, $p + A$ and $A + A$ collisions might be investigated consistently within a hadron–string model without introducing the QGP formation explicitly. An interesting issue arised here is worthy to be studied further. We also plan to improve the agreement between the experimental rapidity and transverse mass distributions and the LUCIAE results via transverse excitations of the string and the intrinsic transverse momentum broadening in the string fragmentation. The investigation for the role played by the hard and semi-hard processes, such as $gg \rightarrow s\bar{s}$ and $q\bar{q} \rightarrow s\bar{s}$ on strangeness enhancement is needed as well.

In summary, the experimentally found ϕ enhancement in $p + \text{Pb}$ and $\text{Pb} + \text{Pb}$ relative to $p + p$ collisions is described consistently by the hadron–string cascade model LUCIAE. In this model, ϕ -mesons are exclusively produced from string fragmentation processes without any further rescattering interactions. However, LUCIAE has employed the mechanisms of the string collective effect (firecracker model) in the gluon emission and of the reduction of s -quark suppression in the string fragmentation. This implies that, at the CERN SPS energy, the ϕ -mesons are mostly produced in primordial collisions and final state interactions at the hadronic stage do not play a significant role.

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